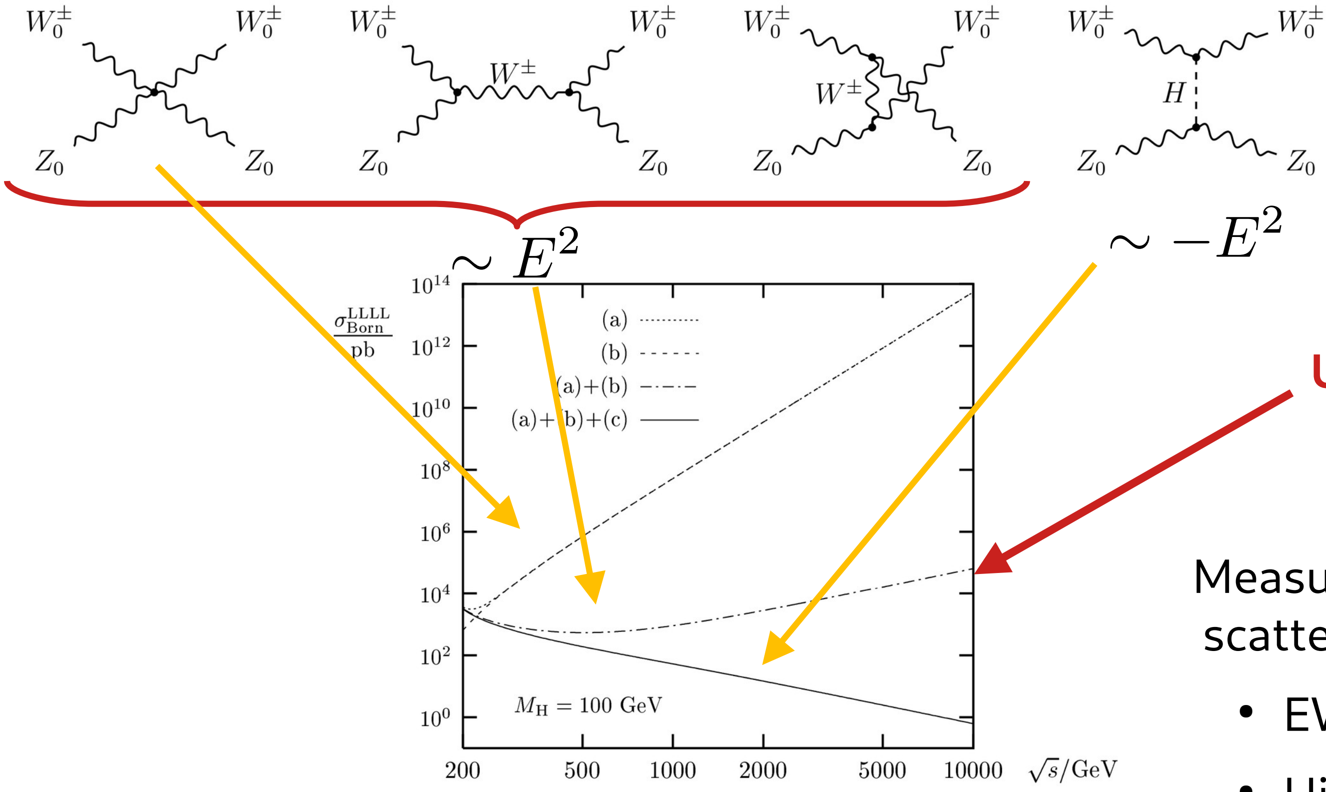
# Polarized predictions in diboson final states

Rene Poncelet

THE HENRYK NIEWODNICZAŃSKI INSTITUTE OF NUCLEAR PHYSICS POLISH ACADEMY OF SCIENCES

COMETA

# Longitudinal Vector-Boson-Scattering (VBS)




**Unitarity violation**

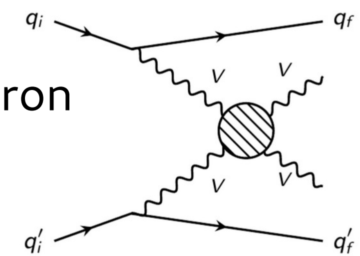
Measurement of polarized boson scattering or production probes:

- EWSB mechanism
- Higgs and gauge sector
- New physics models

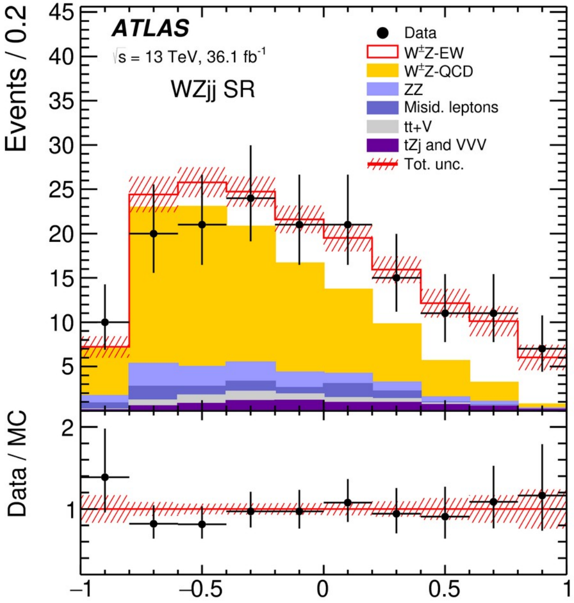
**Radiative corrections to W+ W- → W+ W- in the electroweak standard model**
A. Denner, T. Hahn hep-ph/9711302

# VBS at hadron colliders

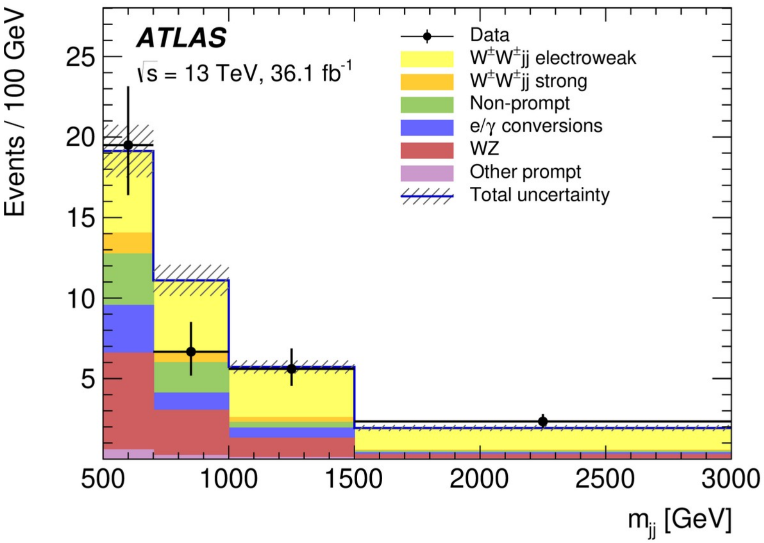
VBS at hadron colliders



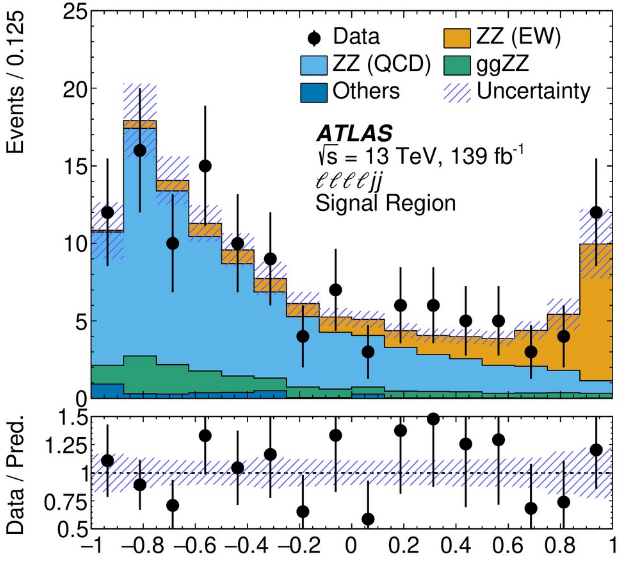

Separate from background processes through VBS topology
→ a rare process, but observed.




WZ (5.3 sigma)
ATLAS 1812.09740




W+W+/W-W- (6.5 sigma)
ATLAS 1906.03203

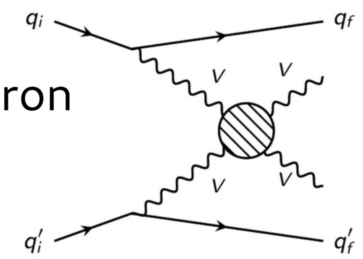



MD

ZZ (5.5 sigma)
ATLAS 2004.10612

# VBS at hadron colliders

VBS at hadron colliders

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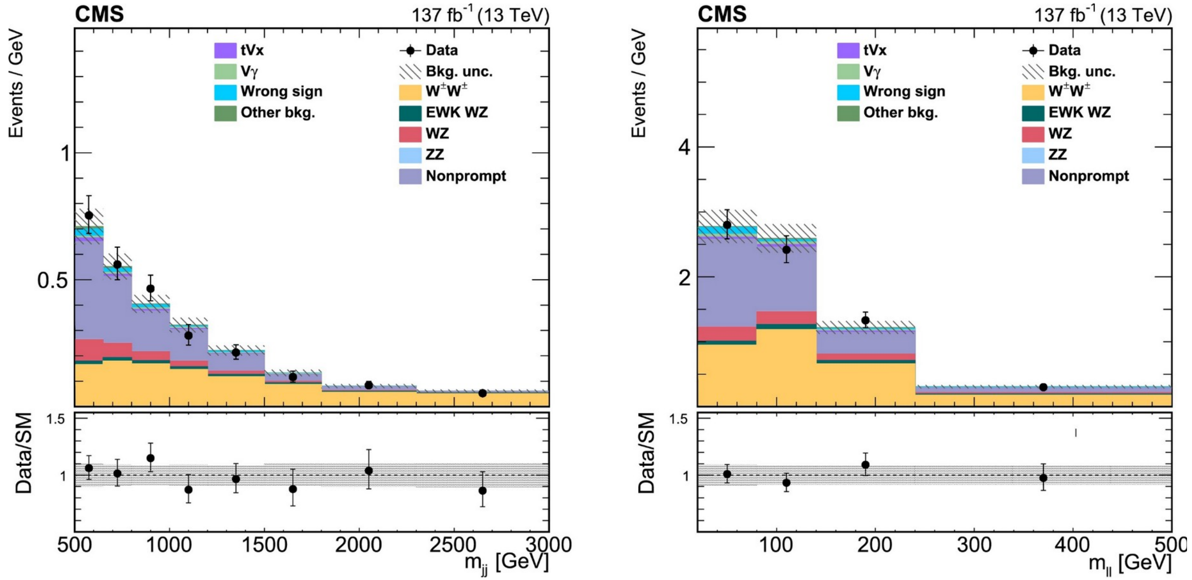
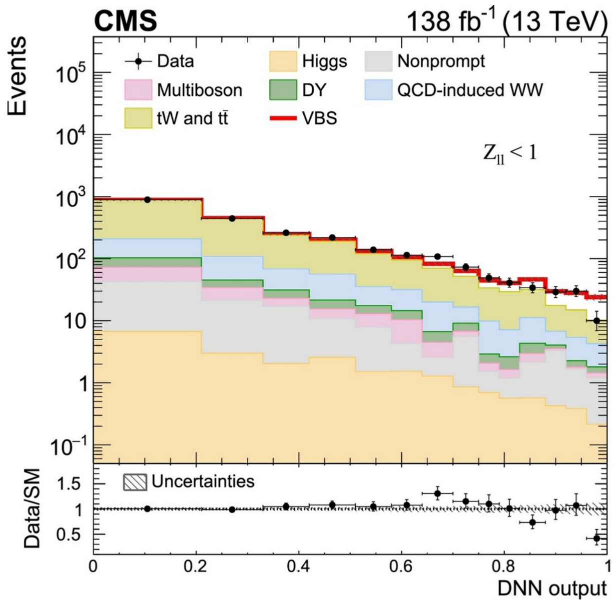



WZ (6.8 sigma) + W+W+/W-W- (diff. xsec)
CMS 2005.01173

W+W- (5.6 sigma)
CMS 2205.05711

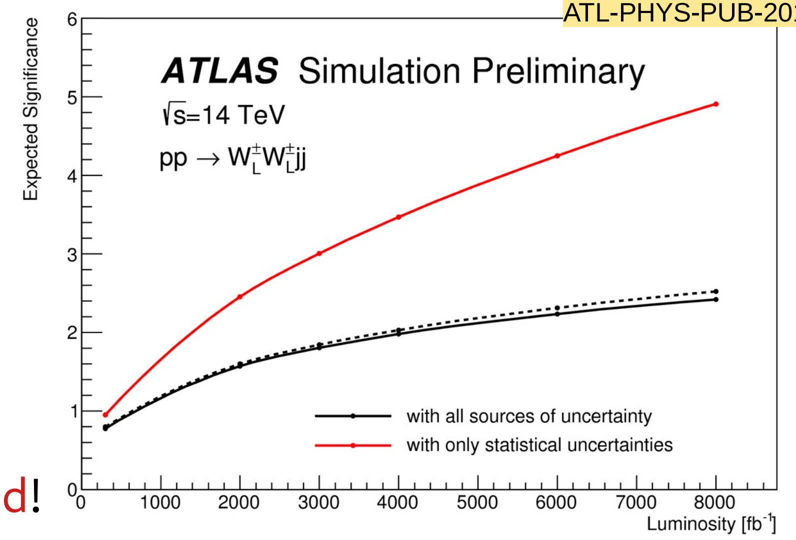
# Polarised VBS at HL-LHC

If we want to study unitarisation/EWSB we need to **extract the longitudinal component**

- only 5-10 % of the total rate
  → very challenging
  (remember: 130fb$^{-1}$ → ~5-7 sigma
  → naive improvement by factor 10 necessary for observation)
- Requires CMS/ATLAS combination and/or new techniques at HL-LHC
  → improvement of systematic uncertainties needed!

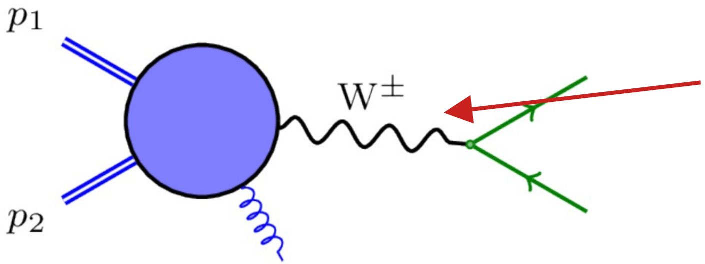
ATLAS HL-LHC projection

ATL-PHYS-PUB-2018-052




How to improve on the (theory) systematics?
→ Improved signal and background (i.e. transverse part)
→ Effective separation of boson polarisation

# Polarised boson production




$$\left(-g^{\mu\nu} + \frac{k^\mu k^\nu}{k^2}\right) \to \sum_\lambda \epsilon^{*\mu}_\lambda \epsilon^\nu_\lambda$$

λ = +/-/L

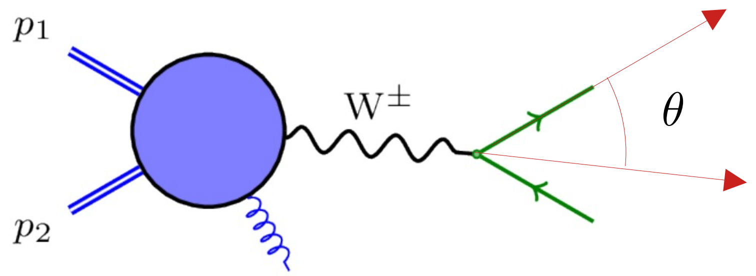
Can we extract the longitudinal component?

Measurements of longitudinal polarisation fractions:

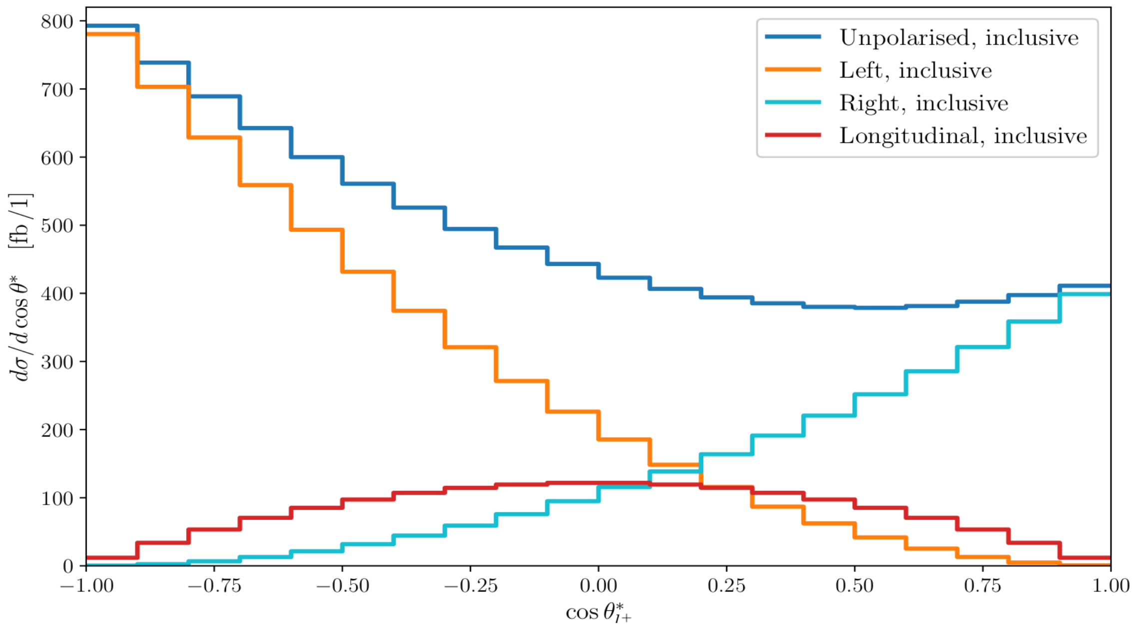
**Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC,**
CMS 1104.3829
**Measurement of the polarisation of W bosons produced with large transverse momentum in pp collisions at \sqrt{s}=7 TeV with the ATLAS experiment,**
ATLAS 1203.2165
**Measurement of WZ production cross sections and gauge boson polarisation in pp collisions at sqrt(s) = 13 TeV with the ATLAS detector,**
ATLAS 1902.05759
**Measurement of the inclusive and differential WZ production cross sections, polarization angles, and triple gauge couplings in pp collisions at sqrt(s) = 13 TeV,**
CMS 2110.11231
**Observation of gauge boson joint-polarisation states in WZ production from pp collisions at sqrt(s) = 13 TeV with the ATLAS detector**
ATLAS 2211.09435

# How to measure polarized bosons?

- We can't measure boson polarization directly.
- Luckily decay products can be used as a "polarimeter":




W+ decay (W- mirrored around 0)



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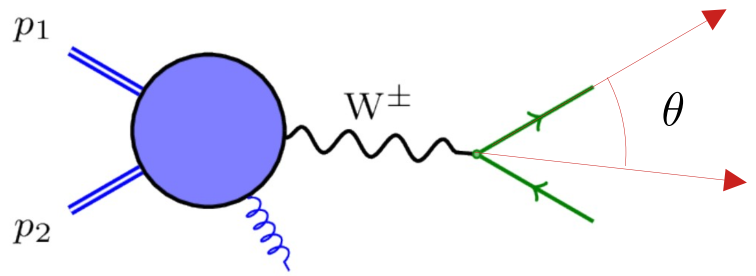


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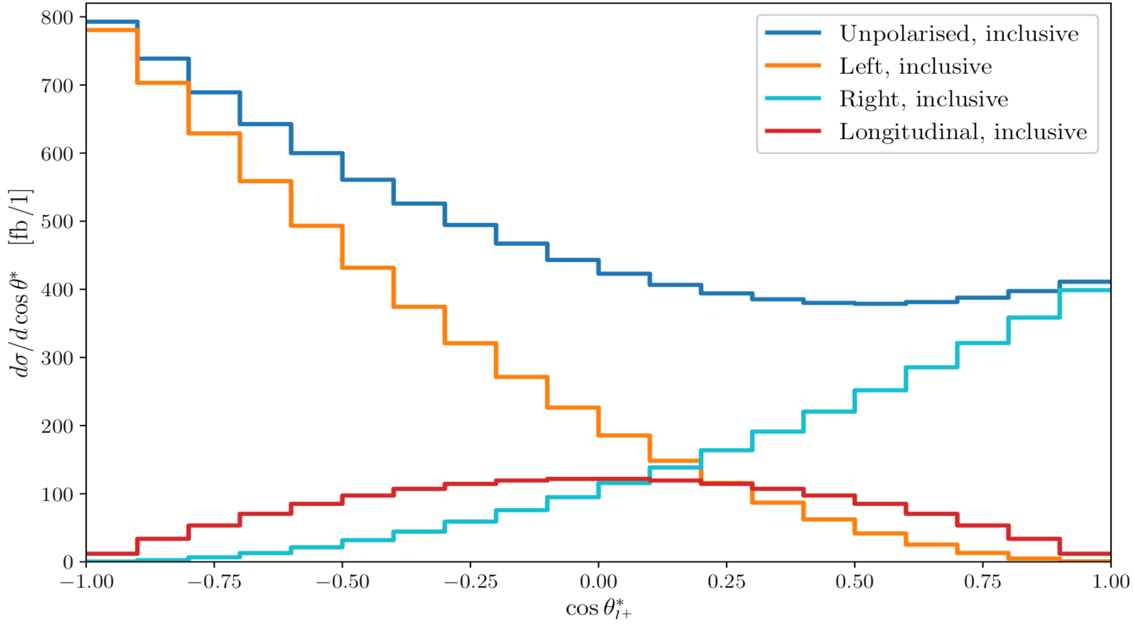
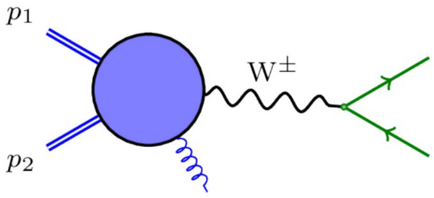


# Polarized cross sections




On-shell bosons: $\left(-g^{\mu\nu} + \frac{k^\mu k^\nu}{k^2}\right) \rightarrow \sum_\lambda \epsilon_\lambda^{*\mu} \epsilon_\lambda^\nu$
(DPA or NWA)

$$M \;= \mathbf{P}_\mu \cdot \frac{-g_{\mu\nu} + \frac{k^\mu k^\nu}{k^2}}{k^2 - M_V^2 + iM_V\Gamma_V} \cdot \mathbf{D}_\nu$$

$$|M|^2 = \underbrace{\sum_\lambda |M_\lambda|^2}_{} + \underbrace{\sum_{\lambda\neq\lambda'} M_\lambda^* M_{\lambda'}}_{}$$

→ polarised x-sections Interferences

Create samples of fixed polarisation: $$\frac{d\sigma}{dX} = f_L \frac{d\sigma_L}{dX} + f_R \frac{d\sigma_R}{dX} + f_0 \frac{d\sigma_0}{dX} \left(+ f_{int.} \frac{d\sigma_{int.}}{dX}\right)$$

Template fit $f_L, f_R, f_0$ to measured $\frac{d\sigma^{exp.}}{dX}$

# Polarized cross sections

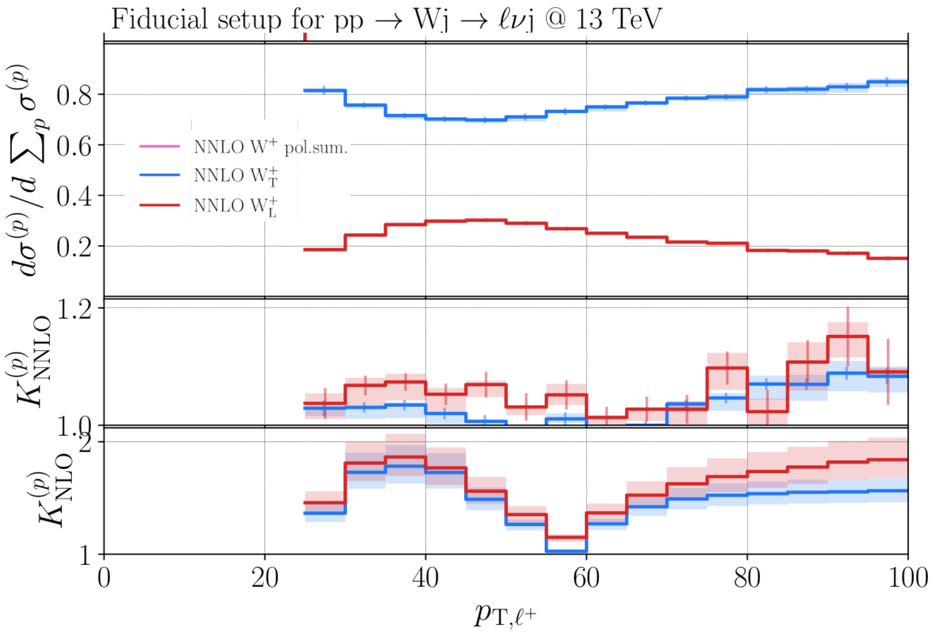
$$\frac{\mathrm{d}\sigma}{\mathrm{d}X} = f_L \frac{\mathrm{d}\sigma_L}{\mathrm{d}X} + f_R \frac{\mathrm{d}\sigma_R}{\mathrm{d}X} + f_0 \frac{\mathrm{d}\sigma_0}{\mathrm{d}X} \left( + f_{int.} \frac{\mathrm{d}\sigma_{int.}}{\mathrm{d}X} \right)$$

- Interferences can be handled
- Does not rely on extrapolations to the full phase space
  X can be any observable → lab frame observables
- $\frac{\mathrm{d}\sigma_i}{\mathrm{d}X}$ can be systematically improved

Higher-order QCD/EW corrections + PS
to minimize uncertainties from MHO (scale uncertainties)

# Why do we need higher-order corrections?

Example: $pp \to W^{\pm}(\to l\nu)j$




**Important**

Just using single NNLO K-factors is not enough

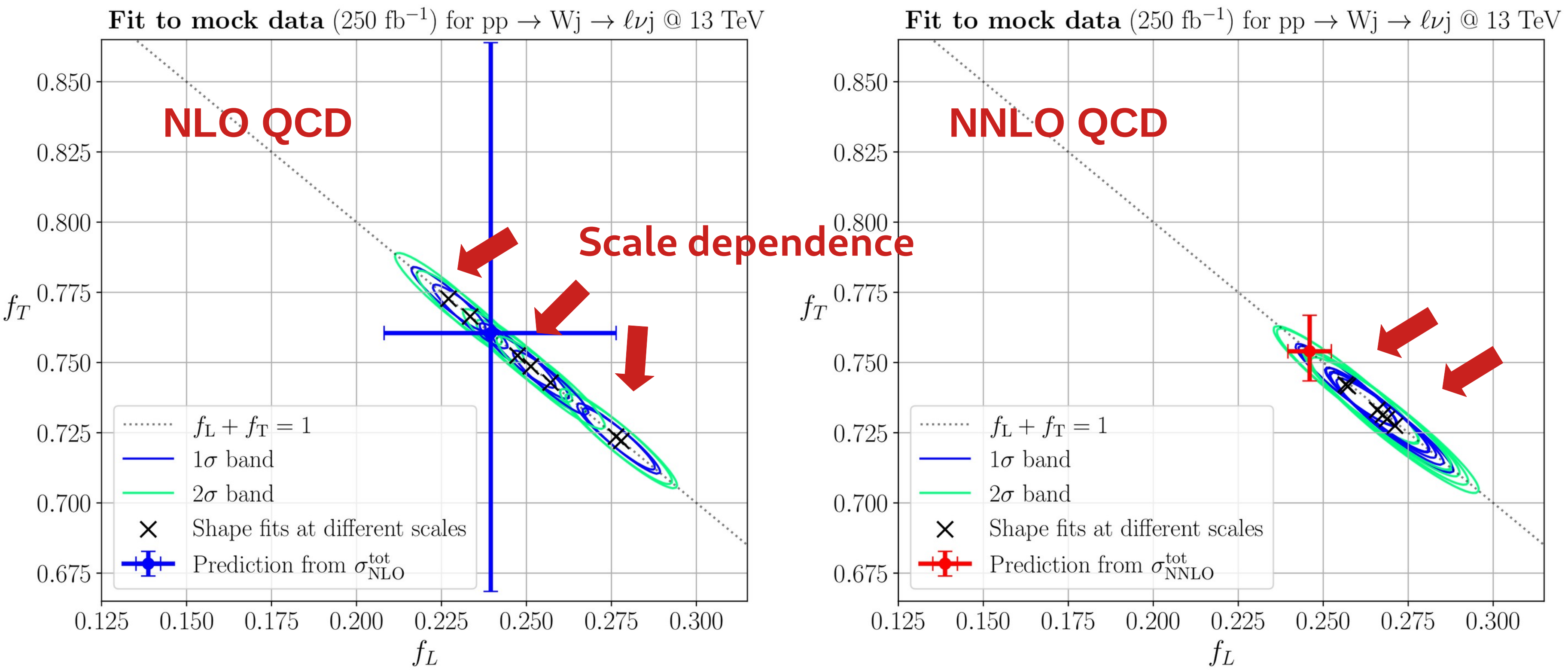
1) Differential polarization fraction have shapes (not just one number!)
2) Higher-order corrections dependent on polarization! Just using unpolarized K-factor would lead to distortion of spectrum.
3) NNLO QCD needed to reach percent-level scale-dependence → MHO

**Polarised W+j production at the LHC: a study at NNLO QCD accuracy**, Pellen, Poncelet, Popescu 2109.14336

# W+jet: mock-data fit

Fit to mock-data (based on NNLO QCD and 250 $fb^{-1}$ stats):
→ extreme case to see effect of scale dependence reduction

Observable: $\cos(\ell, j_1)$



# Status of polarization calculations

| Process | LO | NLO | NLO EW | NNLO | + PS |
|---|---|---|---|---|---|
| pp → WW | X | X | X | X | X |
| pp → ZZ | X | X | X | | X |
| pp → WZ | X | X | X | | X |
| pp → W/Z | X | X | X | Ang. | X |
| pp → W+j | X | X | (X) | X | |
| pp → Z+j | X | Ang. | | Ang. | |
| VBS | X | X | | | |

**(Collection of papers in the backup)**

Ang. = angular coefficients

# Polarised nLO+PS: SHERPA

See also talk by Steffen

**Polarised cross sections for vector boson production with SHERPA**
Hoppe, Schönherr, Siegert 2310.14803

- New bookkeeping of boson polarizations in SHERPA for LO MEs
- Approximate NLO corrections: nLO+PS
  → Reals+matching are treated exact
  → loop matrix elements unpolarised (reweighted by pol. tree MEs)
- Comparison with multi-jet merged calculations

Comparison with fixed order

- nLO+PS approximation in fair agreement with full NLO
  → good for polarization fractions

| $W^+Z$ | $\sigma^{\mathrm{NLO}}$ [fb] | Fraction [%] | K-factor | $\sigma^{\mathrm{nLO+PS}}_{\mathrm{SHERPA}}$ [fb] | Fraction [%] | K-factor |
|---|---|---|---|---|---|---|
| full | 35.27(1) | | 1.81 | 33.80(4) | | |
| unpol | 34.63(1) | 100 | 1.81 | 33.457(26) | 100 | 1.79 |
| Laboratory frame | | | | | | |
| L-U | 8.160(2) | 23.563(9) | 1.93 | 7.962(5) | 23.796(25) | 1.91 |
| T-U | 26.394(9) | 76.217(34) | 1.78 | 25.432(21) | 76.01(9) | 1.75 |
| int | 0.066(10) (diff) | 0.191(29) | 2.00 | 0.064(7) | 0.191(22) | 2.40(40) |
| U-L | 9.550(4) | 27.577(14) | 1.73 | 9.275(16) | 27.72(5) | 1.72 |
| U-T | 25.052(8) | 72.342(31) | 1.83 | 24.156(18) | 72.20(8) | 1.81 |
| int | 0.028(10) (diff) | 0.081(29) | -0.49 | 0.026(7) | 0.079(22) | -0.471(34) |

# Polarised NLO+PS: POWHEG

**Polarised-boson pairs at the LHC with NLOPS accuracy**
Pellicciolі, Zanderighi 2311.05220

- NLO QCD + PS in POWHEG-BOX-RES framework
- Study of PS (Pythia8) + hadronisation effects on fractions and differential distributions WW/WZ/ZZ

→ 1-5% effect on distributions, but generally small impact on fractions (~1% effects)

| state | $\sigma$[fb] LHE | ratio [/unp., %] LHE | $\sigma$[fb] PS+hadr | ratio [/unp., %] PS+hadr |
|---|---|---|---|---|
| Inclusive setup | | | | |
| full off-shell | $98.36(3)^{+4.8\%}_{-3.9\%}$ | 101.20 | $95.27(3)^{+4.9\%}_{-3.9\%}$ | 101.28 |
| unpolarised | $97.20(3)^{+4.8\%}_{-3.9\%}$ | 100 | $94.07(3)^{+4.9\%}_{-3.9\%}$ | 100 |
| LL | $4.499(2)^{+2.8\%}_{-2.3\%}$ | $4.63^{+0.13}_{-0.13}$ | $4.359(2)^{+2.8\%}_{-2.2\%}$ | $4.63^{+0.13}_{-0.13}$ |
| LT | $13.151(4)^{+7.0\%}_{-5.7\%}$ | $13.53^{+0.28}_{-0.27}$ | $12.730(5)^{+7.0\%}_{-5.7\%}$ | $13.53^{+0.28}_{-0.28}$ |
| TL | $12.724(4)^{+7.3\%}_{-5.9\%}$ | $13.09^{+0.32}_{-0.31}$ | $12.314(5)^{+7.4\%}_{-5.9\%}$ | $13.09^{+0.31}_{-0.32}$ |
| TT | $66.88(2)^{+4.0\%}_{-3.3\%}$ | $68.81^{+0.47}_{-0.51}$ | $64.74(2)^{+4.1\%}_{-3.2\%}$ | $68.82^{+0.46}_{-0.51}$ |
| interference | $-0.058$ | $-0.06$ | $-0.069$ | $-0.06$ |

# NNLO QCD polarized WW production

**NNLO QCD study of polarised W+W- production at the LHC,**
Poncelet, Popescu 2102.13583

STRIPPER

Technical aspects:

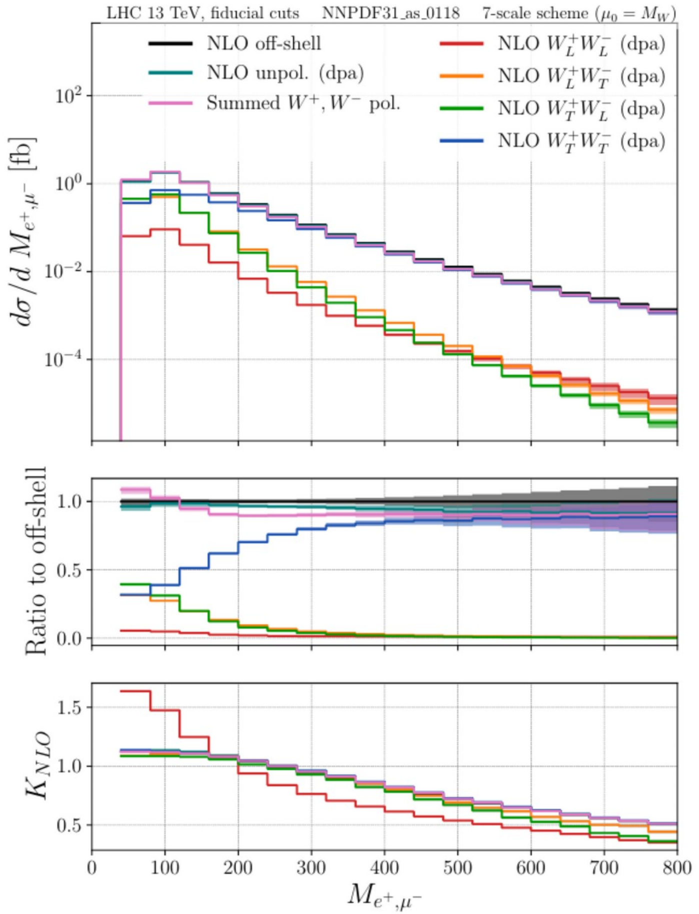
- Implementation of NNLO QCD in c++ sector-improved residue subtraction framework [1408.2500,1907.12911]
- Massive b-quarks → get rid of top production ( $pp \to b\bar{b}W^+W^-$ enters at NNLO)
- NNPDF31 and a fixed renormalisation scale: $\mu_R = \mu_F = m_W$

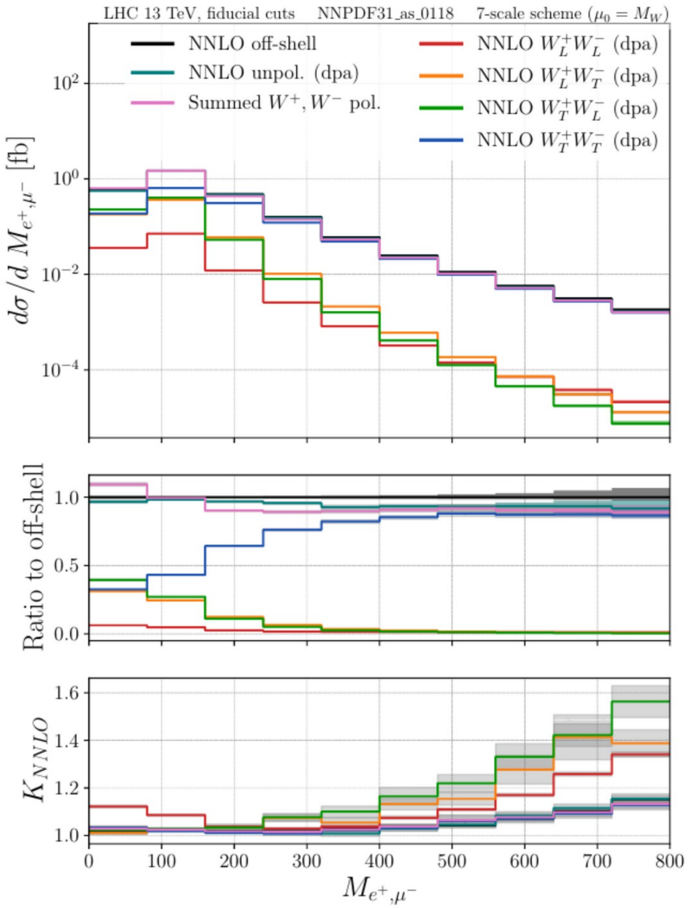
**Measurement of fiducial and differential W+W- production cross-sections at sqrt(s) = 13 TeV with the ATLAS detector**
ATLAS 1905.04242

Fiducial phase space

- Leptons: $p_T(\ell) \geq 27$ GeV $|y(\ell)| < 2.5$ $m(\ell\bar{\ell}) > 55$ GeV
- Missing transverse momentum: $p_{T,\text{miss}} = p_T(\nu_e + \bar{\nu}_\mu) \geq 20$ GeV
- Jet-veto: $p_T(j) > 35$ GeV $|y(j)| < 4.5$

# Polarised di-boson production



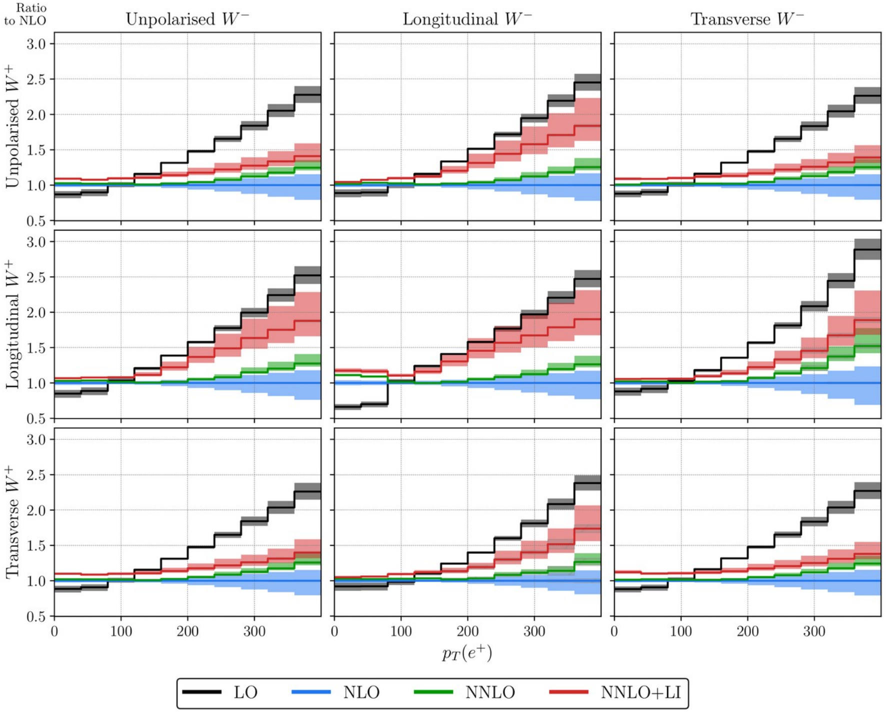
# Doubly polarised cross sections

| | NLO | NNLO | $K_{NNLO}$ | LI | NNLO+LI |
|---|---|---|---|---|---|
| off-shell | $220.06(5)^{+1.8\%}_{-2.3\%}$ | $225.4(4)^{+0.6\%}_{-0.6\%}$ | 1.024 | $13.8(2)^{+25.5\%}_{-18.7\%}$ | $239.1(4)^{+1.5\%}_{-1.2\%}$ |
| unpol. (nwa) | $221.85(8)^{+1.8\%}_{-2.3\%}$ | $227.3(6)^{+0.6\%}_{-0.6\%}$ | 1.025 | $13.68(3)^{+25.5\%}_{-18.7\%}$ | $241.0(6)^{+1.5\%}_{-1.1\%}$ |
| unpol. (dpa) | $214.55(7)^{+1.8\%}_{-2.3\%}$ | $219.4(4)^{+0.6\%}_{-0.6\%}$ | 1.023 | $13.28(3)^{+25.5\%}_{-18.7\%}$ | $232.7(4)^{+1.4\%}_{-1.1\%}$ |
| $W^+_L$ (dpa) | $57.48(3)^{+1.9\%}_{-2.6\%}$ | $59.3(2)^{+0.7\%}_{-0.7\%}$ | 1.032 | $2.478(6)^{+25.5\%}_{-18.3\%}$ | $61.8(2)^{+1.0\%}_{-0.8\%}$ |
| $W^-_L$ (dpa) | $63.69(5)^{+1.9\%}_{-2.6\%}$ | $65.4(3)^{+0.8\%}_{-0.8\%}$ | 1.026 | $2.488(6)^{+25.5\%}_{-18.3\%}$ | $67.9(3)^{+0.9\%}_{-0.8\%}$ |
| $W^+_T$ (dpa) | $152.58(9)^{+1.7\%}_{-2.1\%}$ | $155.7(6)^{+0.7\%}_{-0.6\%}$ | 1.020 | $11.19(2)^{+25.5\%}_{-18.8\%}$ | $166.9(6)^{+1.6\%}_{-1.3\%}$ |
| $W^-_T$ (dpa) | $156.41(7)^{+1.7\%}_{-2.1\%}$ | $159.7(6)^{+0.5\%}_{-0.6\%}$ | 1.021 | $11.19(2)^{+25.5\%}_{-18.8\%}$ | $170.9(6)^{+1.7\%}_{-1.3\%}$ |
| $W^+_L W^-_L$ (dpa) | $9.064(6)^{+3.0\%}_{-3.0\%}$ | $9.88(3)^{+1.3\%}_{-1.3\%}$ | 1.090 | $0.695(2)^{+25.5\%}_{-18.8\%}$ | $10.57(3)^{+2.9\%}_{-2.4\%}$ |
| $W^+_L W^-_T$ (dpa) | $48.34(3)^{+1.9\%}_{-2.5\%}$ | $49.4(2)^{+0.9\%}_{-0.7\%}$ | 1.021 | $1.790(5)^{+25.5\%}_{-18.3\%}$ | $51.2(2)^{+0.6\%}_{-0.8\%}$ |
| $W^+_T W^-_L$ (dpa) | $54.11(5)^{+1.9\%}_{-2.5\%}$ | $55.5(4)^{+0.6\%}_{-0.7\%}$ | 1.025 | $1.774(5)^{+25.5\%}_{-18.3\%}$ | $57.2(4)^{+0.7\%}_{-0.7\%}$ |
| $W^+_T W^-_T$ (dpa) | $106.26(4)^{+1.6\%}_{-1.9\%}$ | $108.3(3)^{+0.5\%}_{-0.5\%}$ | 1.019 | $9.58(2)^{+25.5\%}_{-18.9\%}$ | $117.9(3)^{+2.1\%}_{-1.6\%}$ |

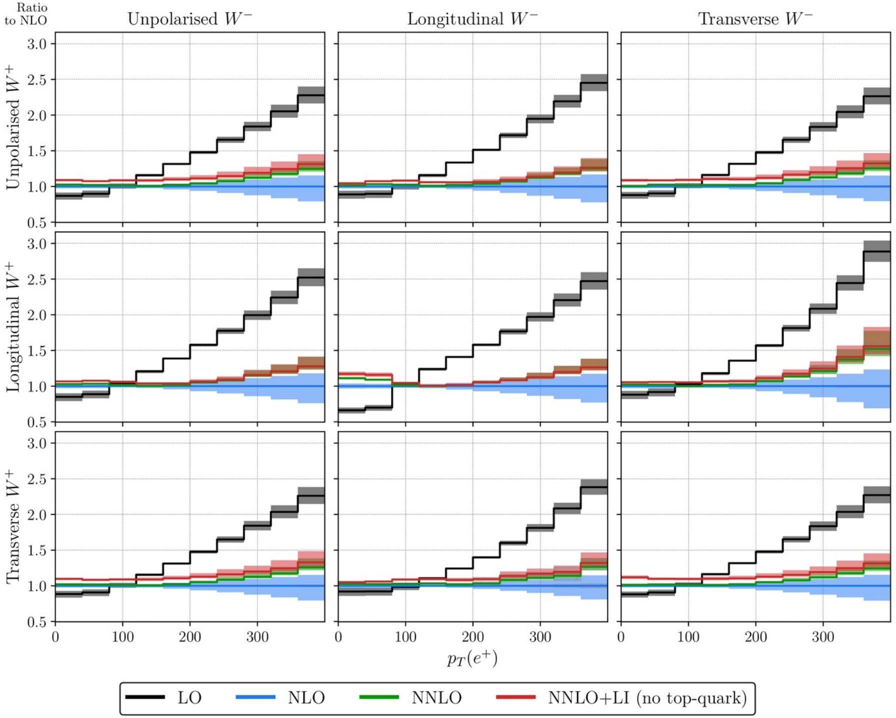
Small LL contribution, with large corrections (→ polarization frame)

# Loop induced gg → WW contributions

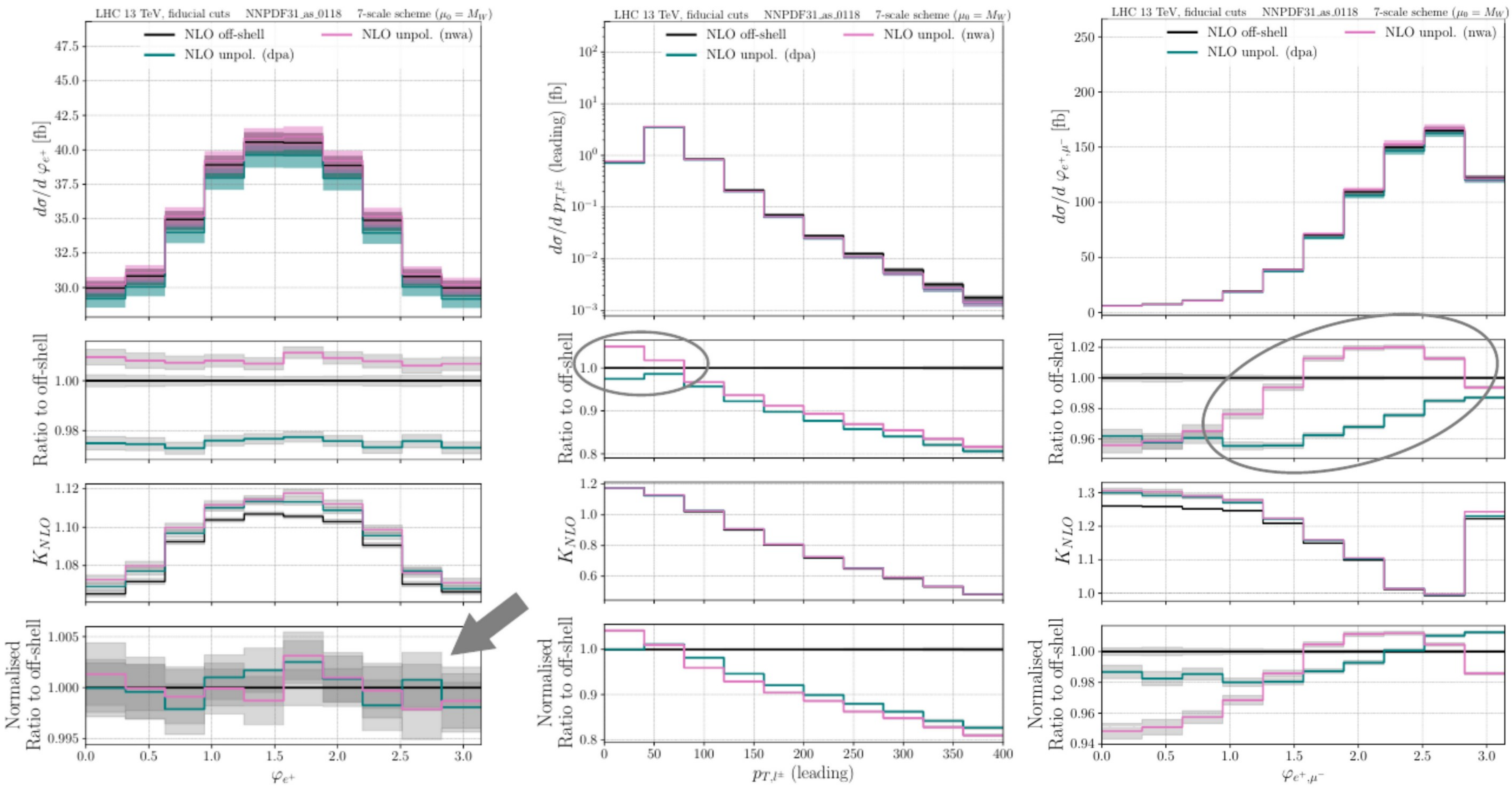
**With top-quark loops in gg LI**




**Without top-quark loops in gg LI**



# NWA vs. DPA


LHC 13 TeV, fiducial cuts NNPDF31_as_0118 7-scale scheme ($\mu_0 = M_W$)
NLO off-shell
NLO unpol. (nwa)
NLO unpol. (dpa)
$d\sigma/d\,\varphi_{e^+}$ [fb]
Ratio to off-shell
$K_{NLO}$
Normalised Ratio to off-shell
$\varphi_{e^+}$
$d\sigma/d\,p_{T,l^\pm}$ (leading) [fb]
$p_{T,l^\pm}$ (leading)
$d\sigma/d\,\varphi_{e^+,\mu^-}$ [fb]
$\varphi_{e^+,\mu^-}$

# Take home messages

- Precise (and accurate) SM predictions for polarized cross section are important to pin down the longitudinal component.
- NLO QCD/EW (+PS) are the state-of-the-art for polarized EW boson processes
  → few process are available at NNLO QCD
- Looking at higher-orders NNLO QCD
  - Scale dependence can mimic signal → NNLO QCD needed to reduce these effects
  - Loop-induced contributions: ‘LO’ at NNLO → needs partial N3LO QCD
- What’s next? → Phenomenology, benchmark new tools (Powheg, SHERPA, Madgraph)
  - NNLO QCD for VV, (+ NLO EW), providing templates through high tea
  - + SMEFT

# COMETA

**Co**mprehensive **M**ultiboson **E**xperiment-**T**heory **A**ction

- WG1 - Theoretical framework, precision calculations and simulation
- WG2 - Technological innovation in data analysis
- WG3 - Experimental Measurements
- WG4 - Management and Event Organization
- WG5 - Inclusiveness and Outreach

Further information:
https://www.cost.eu/actions/CA22130/ and https://cometa.web.cern.ch/

# Backup

# Polarized VV @ (N)NLO QCD / NLO EW

**Fiducial polarization observables in hadronic WZ production: A next-to-leading order QCD+EW study,**
Baglio, Le Duc 1810.11034
**Anomalous triple gauge boson couplings in ZZ production at the LHC and the role of Z boson polarizations,**
Rahama, Singh 1810.11657
**Polarization observables in WZ production at the 13 TeV LHC: Inclusive case,**
Baglio, Le Duc 1910.13746
**Unravelling the anomalous gauge boson couplings in ZW+- production at the LHC and the role of spin-1 polarizations,**
Rahama, Singh 1911.03111
**Polarized electroweak bosons in W+W- production at the LHC including NLO QCD effects,**
Denner, Pelliccioli 2006.14867
**NLO QCD predictions for doubly-polarized WZ production at the LHC,**
Denner, Pelliccioli 2010.07149
**NNLO QCD study of polarised W+W- production at the LHC,**
Poncelet, Popescu 2102.13583
**NLO EW and QCD corrections to polarized ZZ production in the four-charged-lepton channel at the LHC,**
Denner, Pelliccioli 2107.06579
**Breaking down the entire spectrum of spin correlations of a pair of particles involving fermions and gauge bosons,**
Rahama, Singh 2109.09345
**Doubly-polarized WZ hadronic cross sections at NLO QCD+EW accuracy,**
Duc Ninh Le, Baglio 2203.01470
**Doubly-polarized WZ hadronic production at NLO QCD+EW: Calculation method and further results**
Duc Ninh Le, Baglio, Dao 2208.09232
**NLO QCD corrections to polarised di-boson production in semi-leptonic final states**
Denner, Haitz, Pelliccioli 2211.09040
**Polarised cross sections for vector boson production with SHERPA**
Hoppe, Schönherr, Siegert 2310.14803
**Polarised-boson pairs at the LHC with NLOPS accuracy**
Pelliccioli, Zanderighi 2311.05220
**NLO EW corrections to polarised W+W- production and decay at the LHC**
Denner, Haitz, Pelliccioli 2311.16031
**NLO electroweak corrections to doubly-polarized W+W- production at the LHC**
Thi Nhung Dao, Duc Ninh 2311.17027
**Polarized ZZ pairs in gluon fusion and vector boson fusion at the LHC**
Javurkova, Ruiz, Coelho, Sandesara 2401.17365

# Other polarized cross section calculations

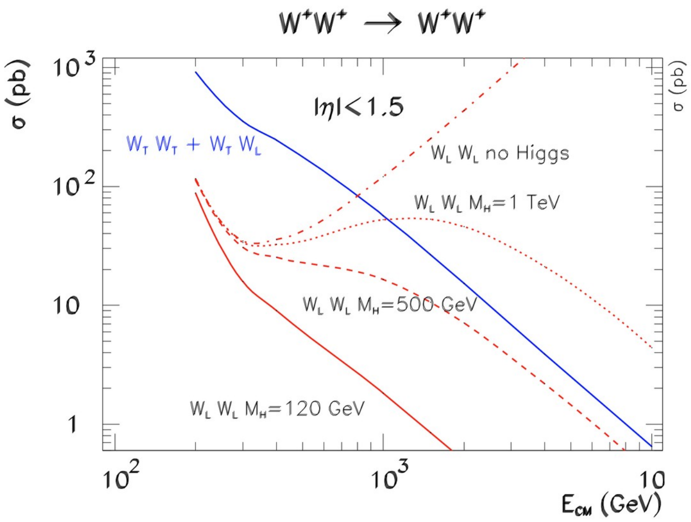
- Polarised VBS (so far LO):
  **W boson polarization in vector boson scattering at the LHC,**
  Ballestrero, Maina, Pellicciol 1710.09339
  **Polarized vector boson scattering in the fully leptonic WZ and ZZ channels at the LHC,**
  Ballestrero, Maina, Pellicciol 1907.04722
  **Automated predictions from polarized matrix elements**
  Buarque Franzosi, Mattelaer, Ruiz, Shil 1912.01725
  **Different polarization definitions in same-sign WW scattering at the LHC**,
  Ballestrero,Maina, Pellicciol 2007.07133

- Single boson production
  **Left-Handed W Bosons at the LHC**,
  Z. Bern et. al. 1103.5445
  **Electroweak gauge boson polarisation at the LHC,**
  Stirling, Vryonidou 1204.6427
  **What Does the CMS Measurement of W-polarization Tell Us about the Underlying Theory of the Coupling of W-Bosons to Matter?**,
  Belyaev, Ross 1303.3297
  **Polarised W+j production at the LHC: a study at NNLO QCD accuracy**,
  Pellen, Poncelet, Popescu 2109.14336

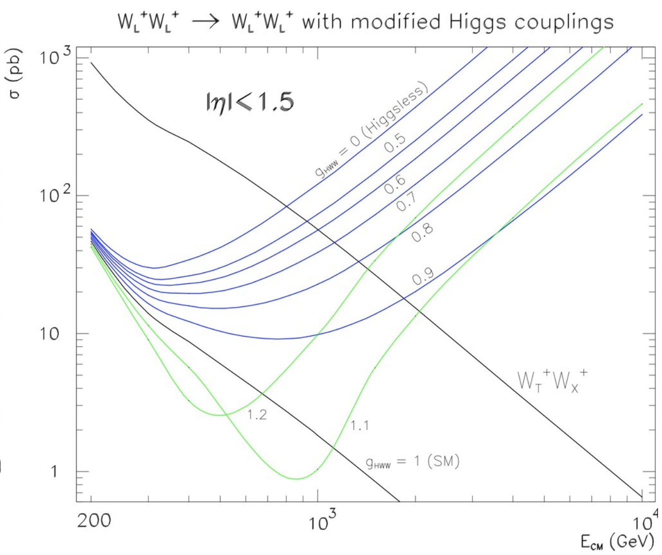
# Longitudinal Vector-Boson-Scattering (VBS)

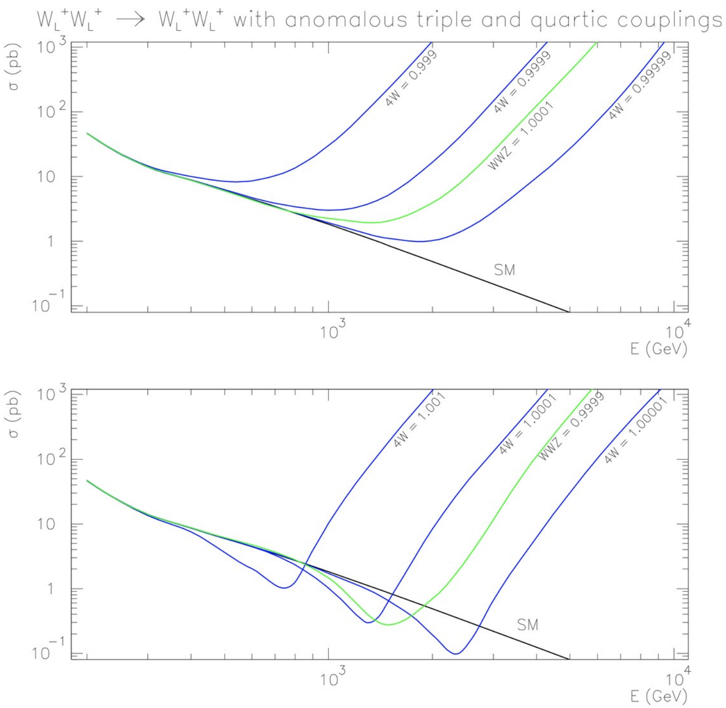
**The Higgs boson and the physics of WW scattering before and after Higgs discovery**
M. Szleper 1412.8367

## Sensitivity to the Higgs mass




## Modified HVV, VVV, VVVV couplings



# EWSB

The reason is the EWSB in the SM:

$$\mathcal{L}_{\mathrm{EW}} = -\frac{1}{4}(W^i_{\mu\nu})^2 - \frac{1}{4}(B^i_{\mu\nu})^2 + (D_\mu\phi)^2 - V(\phi^\dagger\phi)$$

- Higgs potential and minimum:

$$V(\phi^\dagger\phi) = -\mu^2(\phi^\dagger\phi)^2 + \lambda(\phi^\dagger\phi)^4 \qquad \phi = U(\pi^i)\begin{pmatrix} 0 \\ \frac{v+H}{\sqrt{2}} \end{pmatrix}$$

VEV: $\phi^\dagger\phi = \frac{\mu^2}{2\lambda} \equiv \frac{v^2}{2}$

- Goldstone bosons can be absorbed via gauge transformation (unitary gauge). This gives rise to massive gauge bosons:

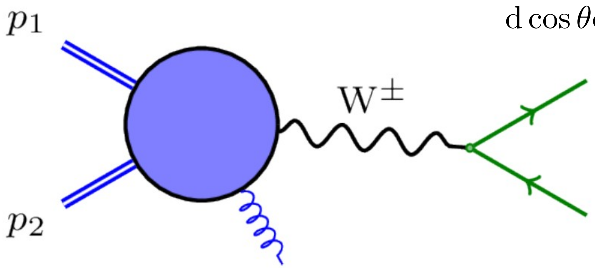
$$\phi = U^{-1}(\pi^i)\phi, \qquad W_\mu = U^{-1}W_\mu U - \frac{i}{g_W}U^{-1}\partial_\mu U$$

$$|D_\mu\phi|^2 \ni \frac{v^2}{8}\left[2g_W^2 W_\mu^+ W^{-\mu} + (g_W W_\mu^3 - g_W' B_\mu)^2\right] \quad \longrightarrow \quad M_W = \frac{1}{2}vg_W\,, \quad M_Z = \frac{M_W}{\cos\theta_W}$$

- Restores renormalizability and unitarity

# Angular coefficients

Angular decomposition of 2-body W decay:




$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta\mathrm{d}\phi\mathrm{d}X} = \frac{\mathrm{d}\sigma}{\mathrm{d}X}\frac{3}{16\pi}\Big[(1+\cos^2\theta) + \frac{A_0}{2}(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{A_2}{2}\sin^2\theta\cos 2\phi$$
$$+ A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big]$$

After azimuthal integration:

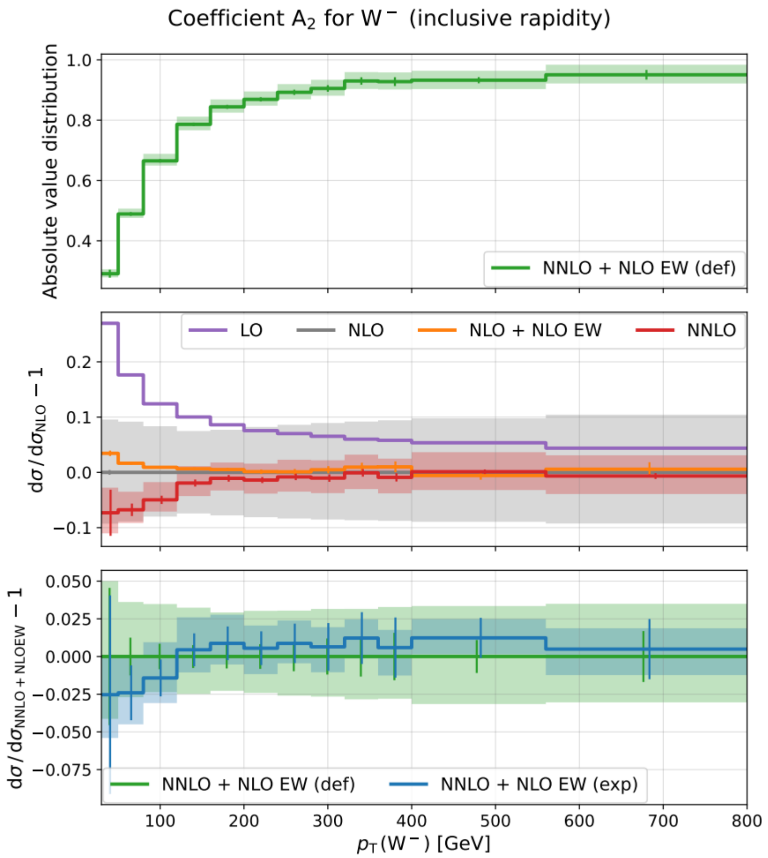
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\cos\theta} = \frac{3}{4}\sin\theta f_0 + \frac{3}{8}(1-\cos\theta)^2 f_L + \frac{3}{8}(1+\cos\theta)^2 f_R$$

Idea: Suitable projections (or fits) extract fractions of left, right and longitudinal components.

# Angular coefficients as function of V kinematics

Keeping azimuthal dependence & boson kinematics:

$$\frac{d\sigma}{dp_{T,W}\, dy_W\, dm_{\ell\nu}\, d\Omega} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_{T,W}\, dy_W\, dm_{\ell\nu}} \Bigg( (1+\cos^2\theta) + A_0 \frac{1}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + A_2 \frac{1}{2} \sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \Bigg),$$



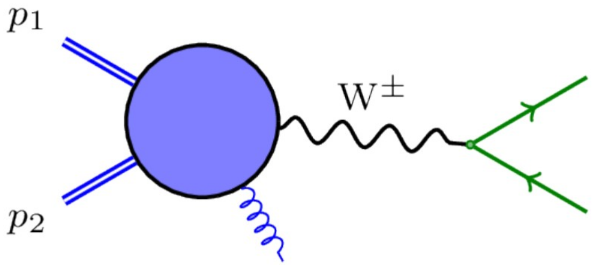

**Angular coefficients in W+j production at the LHC with high precision**
Pellen, Poncelet, Popescu, Vitos, 2204.12394

# Angular coefficients, practical considerations

This simple idea suffers from:

- Fiducial phase space requirements on the leptons:
  → Interferences do not cancel
  → Correspondence between fractions ( $f_0, f_L, f_R$) and angular distributions broken.
- Higher order corrections to decay (QED radiation or QCD in hadronic decays)
  → Decomposition in $\{A_i\}$does not hold any more
- Angles in boson rest frame
  → Z rest frame accessible, but W more difficult to reconstruct

# Polarised W+jet cross sections




Why looking at polarised W+jet with leptonic decays?

- The EW part is simple:
  - no non-resonant backgrounds
  - neutrino momentum approx. accessible (missing ET)
- Large cross section → precise measurements

Goals:

- Use W+j data to **extract the longitudinal polarisation fraction** (done before by exp.)
  → understand impact of NNLO QCD corrections (reduced scale dependence)
- Study **inclusive** (in terms of W decay products) and **fiducial** phase spaces
  → How does the sensitivity to longitudinal Ws depend on this?
  Which observables have **small interference/off-shell** effects?
- Are there any differences between W+ and W-?
  From PDFs and the fact that we cut on the charged lepton?

# Setup W+jet: LHC @ 13 TeV

**Polarised W+j production at the LHC: a study at NNLO QCD accuracy**, Pellen, Poncelet, Popescu 2109.14336

Inclusive phase space:

- At least one jet with $|y(j)| \leq 2.4$ and $p_T(j) \geq 30$ GeV

Fiducial phase space:

**Measurement of the differential cross sections for the associated production of a W boson and jets in proton-proton collisions at \sqrt{s}=13 TeV,** CMS 1707.05979

- Lepton cuts: $p_T(\ell) \geq 25$ GeV, $|\eta(\ell)| \leq 2.5$ and $\Delta R(\ell, j) > 0.4$
- Transverse mass of the W: $M_T(W) = \sqrt{m_W^2 + p_T^2(W)} \geq 50$ GeV

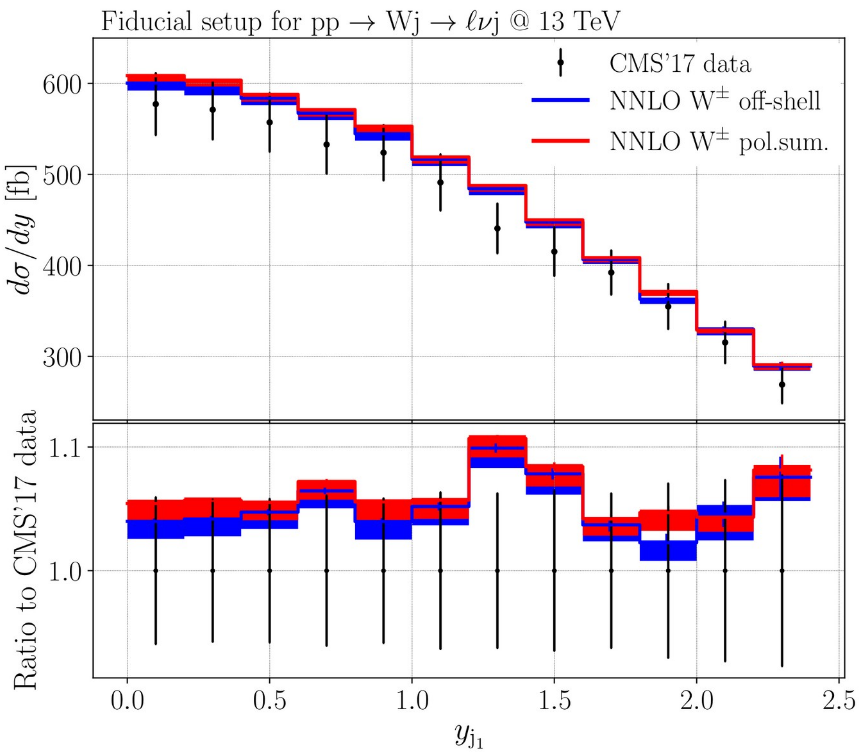
Technical aspects:

- NNPDF31 and dynamical scale choice: $\mu_R = \mu_F = \frac{1}{2}\left(m_T(W) + \sum p_T(j)\right)$
- Implementation in STRIPPER framework (NNLO QCD subtractions) [1408.2500]
  - Narrow-Width-Approximation and OSP/Pole-Approximation
  - Matrix elements from: AvH[1503.08612], OpenLoops2 [1907.13071](cross checks with Recola [1605.01090]) and VVamp [1503.04812]

# Extraction of polarisation fractions

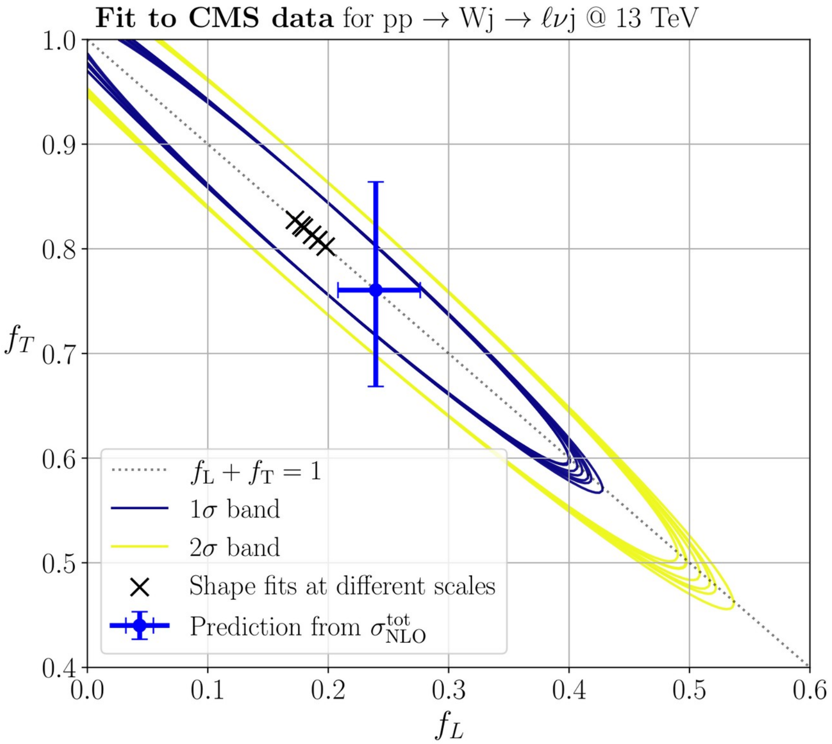
Identified 4 observables (ranges) with
→ Small interference effects (<2%)
→ Small off-shell effects (<2%)
→ Shape differences between L and T

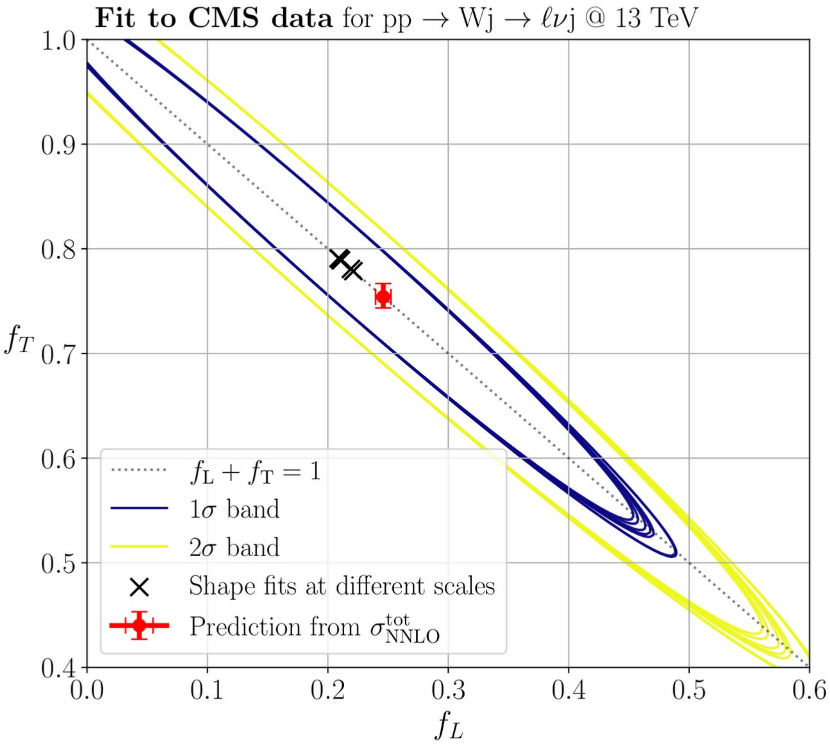
- $\Delta\phi(\ell, j_1) \geq 0.3$
- $25 \text{ GeV} \leq p_T(\ell) < 70 \text{ GeV}$
- $\cos(\theta^*_\ell) \geq -0.75$
- $|y(j_1)| \leq 2$



# W+jet : fit to CMS data

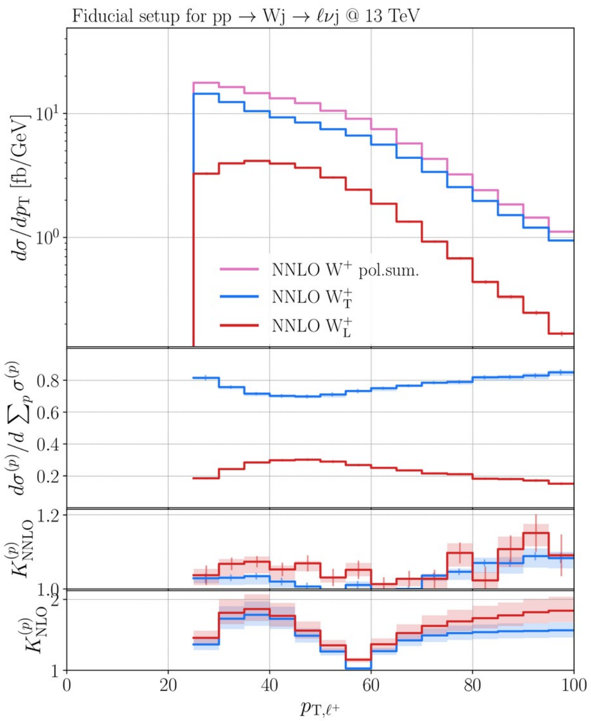
Fit to actual data, here $|y(j_1)|$
→ dominated by experimental uncertainties (no correlations available)



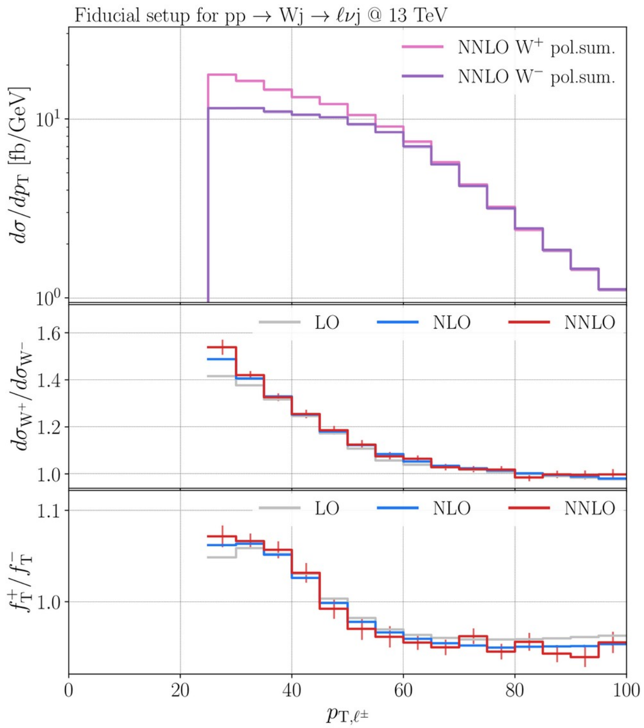



# Example: lepton transverse momentum

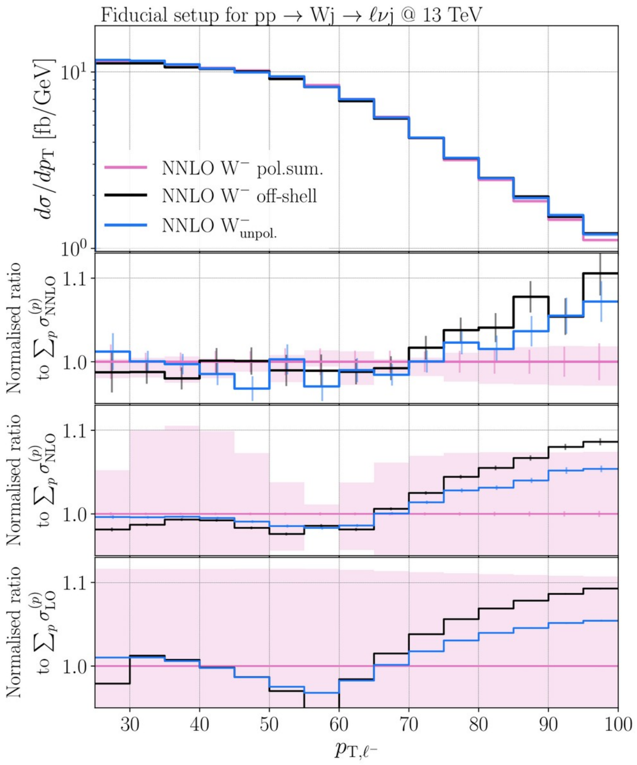
Perturbative corrections



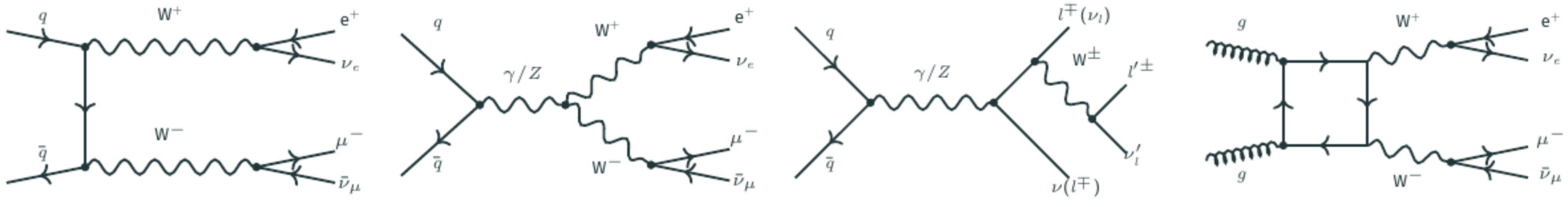

Charge differences




Off-shell/Interference effects

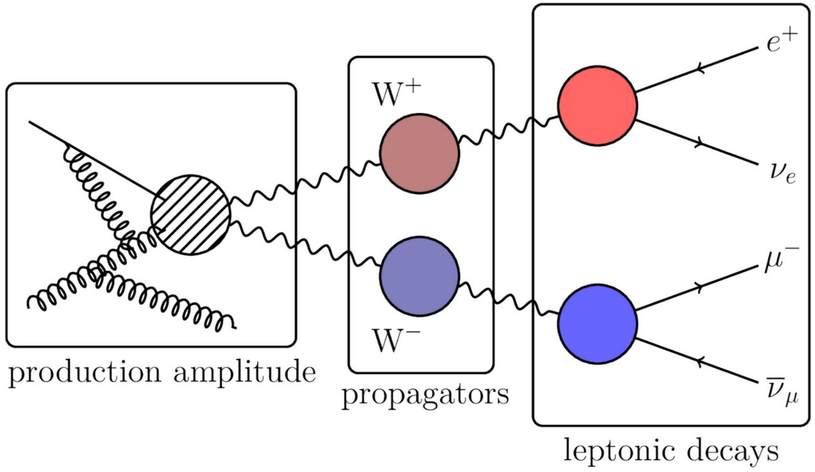


# W-boson pair production



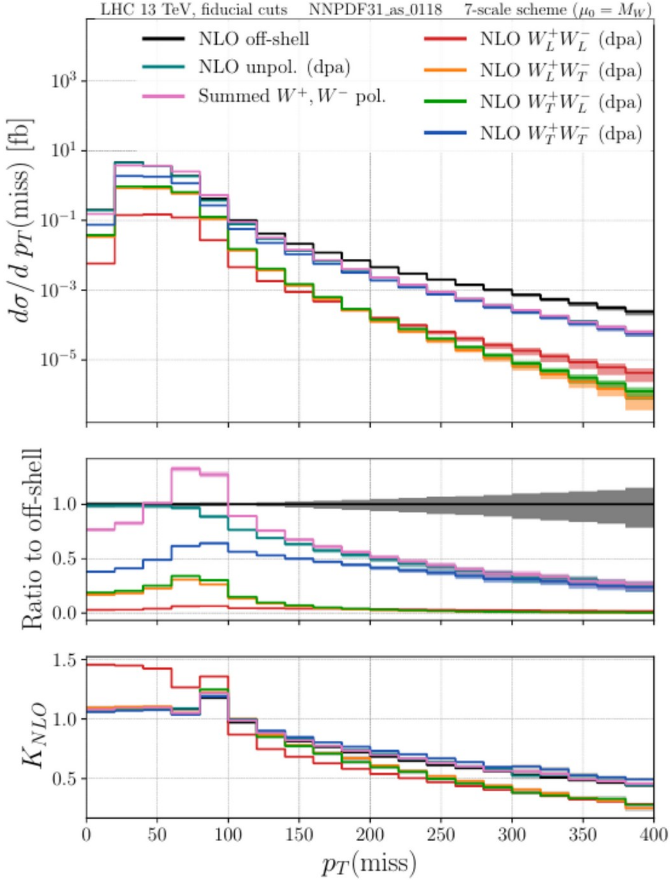

Double resonant (DR) | Double resonant (DR) | Single resonant (SR) | Loop-induced (LI)

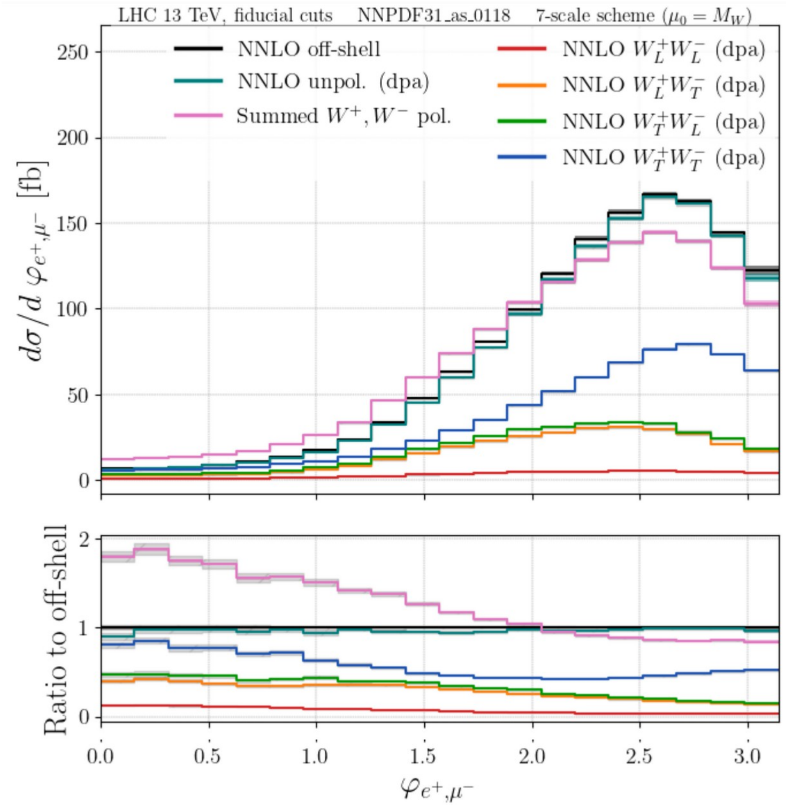
- Single resonant backgrounds: Definition of polarizations states in DPA [1710.09339] and NWA
- LI enters at NNLO → large corrections



# Interference and off-shell effects

Large off-shell effect from single-resonant contributions




Large interference effects through phase space constraints